Mody University of Science and Technology

Lakshmangarh

Faculty of Engineering and Technology

Efficient Design of VCOs and its Applications

Research Proposal Approved by the SRC held on 27.09.2014

Research Proposal

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Chapter – 1

VOLTAGE CONTROLLED OSCILLATOR

1.1 Introduction:

A voltage-controlled oscillator (VCO) is one of the most important basic building blocks for analog and digital circuits. There are many different implementations of VCOs. One of them is the ring oscillator based VCO, which is commonly used in the clock generation subsystem. The main reason of the popularity of ring oscillator is a direct consequence of its easy integration. Due to their integrated nature, ring oscillators have become an essential building block in many digital and communication systems. The design of a ring oscillator involves many tradeoffs in terms of speed, power, area, and application domain. A VCO is the most important part of wired and wireless communication system. Wireless applications require oscillators that must be tunable. It is an oscillator whose output frequency is controlled by a voltage input. The Block diagram of voltage controlled oscillator is shown in Fig.1.

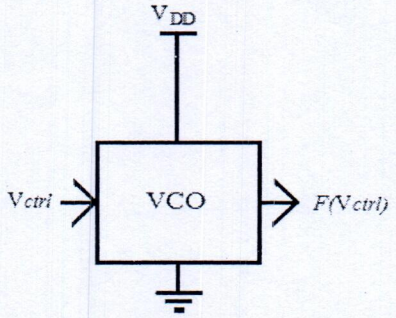

Fig. 1 Block diagram of VCO

VCOs are electronic circuits which are used for high speed clock generation, channel selection and frequency modulation and demodulation in communication systems.

The output frequency of VCO is given by:

$$f_{Out} = f_o + K_{VCO} V_{ctrl} \quad (1)$$

Where, f_o is centre frequency of the VCO, it is the frequency at which VCO will oscillate with no external control. It is also referred as the free-running frequency and K_{VCO} is the sensitivity or gain of the VCO that controls how much a change in control voltage will

change the VCO's frequency. V_{ctrl} is the input to the VCO that sets it to the desired frequency. The output frequency variation with control voltage for ideal VCO is shown in Fig. 2. The achievable output frequency range $F_2 - F_1$ is the tuning range of the VCO [1].

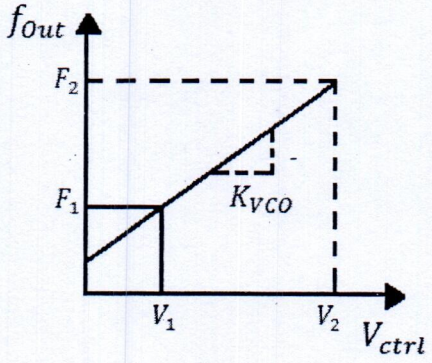

Fig. 2 Output frequency variation with control voltage for ideal VCO

The general requirements for ideal VCO include high spectral purity, linear voltage-to-frequency transfer characteristic, and good frequency stability to power supply and temperature variation. It is integral part of many electronic systems. Applications range of VCO from clock generation in function generators to carrier synthesis in telephones, requiring vastly different types of VCOs topologies and performance parameters. Robust, high performance oscillator design in CMOS technology continues to pose interesting challenges [2-4].

1.2 Performance Metrics:

The performance of any integrated circuit (IC) is determined by a set of parameters that are relevant to the application. For VCOs the parameters we have considered are briefly discussed in this section.

1.2.1 Power Dissipation:

Low power design has become favourable to keep battery powered devices running for longer times on a single charge while keeping the devices light and mobile. Secondly as the power consumption increases more heat is dissipated which may result in shorter life span of the device. Hence power dissipation is an important parameter which needs to be taken in to account while selecting a particular oscillator topology.

1.2.2 Jitter:

Jitter is the variation of the clock edges at the oscillator's output and introduces uncertainty in the output. In many applications jitter is the most important parameter considered while selecting oscillator architecture. In ROs, flicker and white noise are main causes of jitter. The induced jitter also depends on the oscillation frequency and transistor dimensions but is independent of the number of the oscillator stages.

1.2.3 Area:

The objective of technology scaling is to integrate as many system components as possible on a single chip so it is desirable that the circuit occupies small area while satisfying the other performance metrics.

1.2.4 Tuning Range:

Another important parameter of interest especially for the VCOs is the output frequency tuning range. The frequency tuning range is classified in two schemes that are coarse and fine tuning.

1.2.5 Oscillation Frequency:

The oscillation frequency of all the architectures under consideration is almost in the same range but vary due to the complexity of the control schemes employed. Hence the choice of the control scheme would also depend on the required oscillation frequency [5].

1.3 Barkhausen Criterion for Sustained Oscillation:

The basic components in a feedback oscillator are the amplifier and a positive feedback network. Usually the amplifier acts as the amplitude-limiting component, and the frequency-determining network performs the feedback function. The simple positive feedback system is shown in Fig. 3.

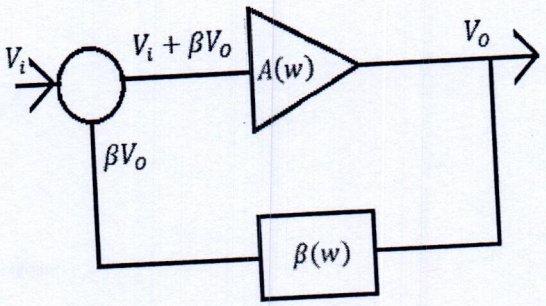

Fig. 3 Simple positive feedback system

The equation for this circuit is given by:

$$V_0 = A(V_i + \beta V_0) \tag{2}$$

The oscillator loop gain is given by:

$$\frac{V_0}{V_i} = \frac{A}{1 - A\beta} \tag{3}$$

Where, A= open loop gain and β = feedback factor

The feedback network feeds a fraction of the amplifier output back to its input in such a way as to satisfy the two fundamental requirements for occurrence of sustained oscillation.

- The magnitude of loop gain is unity, which ensure that the feedback signal has the same magnitude as that of input signal.($|A\beta|=1$)
- The magnitude of loop phase shift is such that the feedback signal is in phase with input signal [5].

1.4 Classification of Voltage Controlled Oscillator:

Oscillators is electronic circuits that produce a stable periodically time varying waveform. There are two different topologies for controlled oscillators on silicon ICs:

- Ring Oscillator ,
- Tuned or LC Oscillator

1.4.1 Ring Oscillator:

A ring oscillator is a device composed of an odd number of NOT gates whose output oscillates between two voltage levels, representing true and false. The NOT gates, or inverters, are attached in a chain; the output of the last inverter is fed back into the first. Their prime advantages are their full integrability into a die and their wide operating frequency range. The oscillation frequency is directly related to the delay time of each inverter, resulting in high sensitivity to process and temperature variations[2].

1.4.2 Tuned or LC Oscillator:

LC oscillators are characterized by equivalence to two energy storage elements operating in resonance to produce a periodic output signal. The resonant element is typically either a LC tank or a quartz crystal. These types of oscillators are known to, have excellent jitter performance. The drawback that these oscillators suffer from is the fact that the LC tank and crystals have to be off-chip. This defeats the purpose of trying to develop integrated VCOs. Nowadays, integrated inductors are commonly used in designs but they consume large amounts of die real estate. Even then, these inductors typically suffer from low Q values due to resistive losses. This has the effect of degrading the jitter performance of these oscillators. The oscillation frequency of LC oscillators is dependent upon the inductance and capacitance of the resonant elements according to Equation (4).

$$F_{osc} = \frac{1}{2\Pi\sqrt{LC}} \tag{4}$$

1.5 Ring versus LC Voltage Controlled Oscillator:

When choosing VCO architecture, one must determine the specifications related to the VCO characteristics, and then decide whether a ring or LC VCO would better suit the application, as they each have their strengths and weaknesses.

1.5.1 Phase Noise:

`Phase noise is often the most important specification that must be met when choosing VCO architecture. If excellent phase noise characteristics are required, an LC VCO will usually

be necessary. Two of the main parameters related to phase noise are the attainable quality factor of the oscillator and the oscillator's ability to reject supply and substrate noise. The quality factor, of an oscillator is inversely proportional of phase noise. It means that higher Q reduces the phase noise.

The quality factor 'Q' of an oscillator is related to the loss of the circuit, and a common definition is given:

$$Q = 2\pi \frac{energy\ stored}{enerrgy\ dissipated\ per\ cycle} \qquad (5)$$

An LC oscillator will have a higher Q than a ring oscillator. The reason can be seen by analyzing the energy storage and dissipation during a cycle. In an ideal LC oscillator, the energy will transfer between the inductive and capacitance elements with no loss, resulting in an infinite Q. In a practical LC oscillator, there are losses associated with each element, such as series resistance losses in the inductor, but energy still switches between the two reactive elements. However, in a ring oscillator, the energy is stored in the equivalent capacitance of the next stage, and the energy is fully charged and then discharged every cycle.

1.5.2 Maximum Frequency:

A second specification is the maximum frequency of the VCO. An LC tank has a higher maximum attainable frequency than a ring oscillator. The oscillation frequency of an LC tank is inversely proportional to the square root of L and C. The value of these elements can be made extremely low, and therefore the frequency of the tank very high. However, active devices are still needed to maintain oscillation, and can limit the frequency.

1.5.3 Tuning Range:

Wireless application requires that oscillator be tunable, if a high tuning range is needed, a ring oscillator should be used. There are numerous parameters that can be varied to change the frequency of the ring oscillator, and many of these parameters can be varied over a wide range. The tuning range for ring oscillators can reach over 50%. However, typically, the only parameter varied in a monolithic LC tank is the capacitance of the varactor. This tends to result in a tuning range of less than 20%.

1.5.4 Manufacturability:

There are two issues related to the manufacturability of the VCO. These are how easily the VCO can be integrated into a monolithic solution, and how much the centre frequency will vary over process parameters. A ring oscillator is preferred if die area is a large concern. Monolithic inductors can occupy a large area, which corresponds to higher cost. However, the centre frequency of a ring oscillator can also vary by more than an LC tank due to process variations. Even with this larger variation, ring oscillators are still more likely to be able to be used at the desired frequency because of their wide tuning range.

Table I. LC versus Ring Oscillator

Properties	**LC or Tuned Oscillator**	**Ring Oscillator**
Layout Area	High	Lowest
Tuning Range	Narrow	Very Wide
Jitter Performance	Excellent	Fair
Integrability	Poor	Good

As shown in Table I. LC oscillators have better phase noise performance than ring oscillators but the latest trends demand the design with easy implementation of the circuit, small chip area, low cost and good performance. The implementation of high quality inductor and capacitor in a standard CMOS process requires extra non standard processing steps and also increases the chip area and the cost. On the other hand, ring oscillators are completely integrated circuits [1-2].

1.6 Types of Ring Oscillator:

Ring oscillators are often used in high-speed digital circuits for clock generation. Several reasons justify this popularity, one of them is wide tuning range, which can be easily obtained with a ring oscillator; another reason is, ring oscillators are compatible with digital CMOS technology and occupy substantially less area than LC oscillators. Ring VCO is further classified into two parts that are:

- Single ended Ring Oscillator
- Differential Ring Oscillator

1.6.1 Differential Ring Oscillator:

A VCO using differential delay stages have an even number of stages if the feedback lines are swapped. The extra required phase shift (π) can be obtained by reversing one of the connections in architecture introducing a DC phase inversion. Fig. 4 shows a four stage differential ring oscillator where DC phase inversion is between the fourth and first stage [2-5]. The block diagram of differential Ring VCO is shown in Fig. 4.

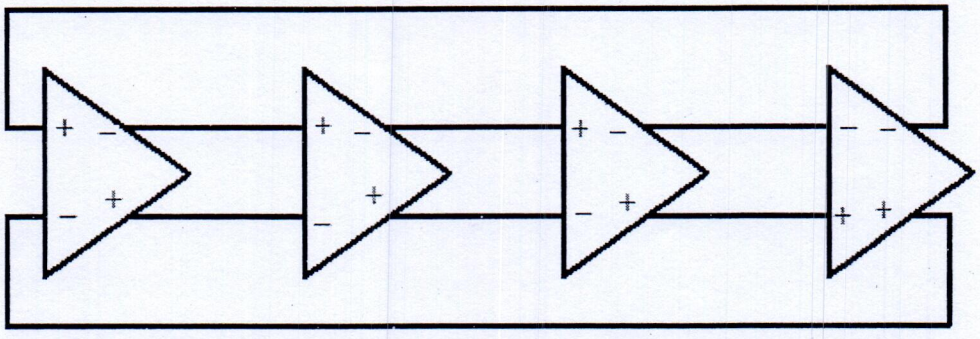

Fig. 4 Block diagram of four stage differential Ring VCO

1.6.2 Single Ended Ring Oscillator:

The delay cell for the single ended Ring Oscillator has the highest frequency of oscillation and minimum power dissipation. In single ended ring based oscillator design output of last stage is fed back to input of first stage. To achieve oscillation, the ring must provide a phase shift of 2π and should have unity voltage gain. Each delay stage should provide phase shift of π/N, where N is number of delay stages. The remaining π phase shift is provided by dc inversion. This means that for an oscillator with single-ended delay stages, an odd number of stages are an important condition for the dc inversion. The Ring oscillator using single ended inverter is shown in Fig. 4.5.

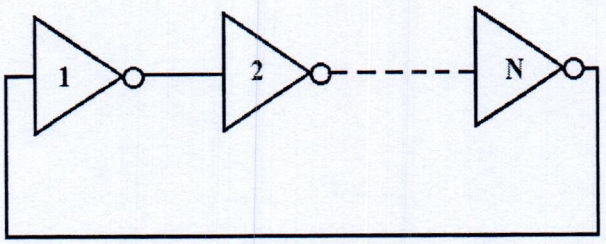

Fig. 5 Single ended N stage Ring Oscillator

To see why this circuit will oscillate, assume that the output of the first inverter is a 0. Therefore, the output of the N^{th} inverter, where N is odd, must also be 0. However, this output is also the input to the first inverter, so the first inverter's output must switch to a 1. By the same logic, the output of the last inverter will eventually switch to a 1, switching the output of the first inverter back to 0. This process will repeat indefinitely, resulting in the voltage at each node oscillating.

To determine the frequency at which this circuit will oscillate, the delay provided by each inverter cell is t_d. The signal must go through N inverters, each with the delay t_d, for a total time of Nt_d, to obtain the first 2 π phase shift. Then, the signal must go through each stage a second time to obtain the remaining π phase shift, resulting in a total period of $2Nt_d$ [1] [2] [7]. The frequency is the reciprocal of the period, resulting in the frequency as:

$$F_O = \frac{1}{2Nt_d} \tag{9}$$

Where N is the total number of delay stages and t_d is delay of each stage.

1.7 Applications of Voltage Controlled Oscillator:

Voltage controlled ring oscillators are core structure in analog and digital systems. It is mostly used in:

- Function generators.
- RF and wireless systems - In the wireless transmission systems, the VCO is used for the frequency synthesizer to generate the local oscillating signal for the modulation and demodulation of the RF signal.
- To generate variable tones.
- Ring oscillators can also be used to measure the effects of voltage and temperature on a chip.

- Many wafers include a ring oscillator as part of the scribe line test structures. They are during wafer testing to measure the effects of manufacturing process variations.
- Temperature sensor.
- Spread spectrum.
- Hardware random number generators.
- Disk-drive read channels.
- Analog to digital convertors.
- Static random access memory
- Clock and data recovery circuits.
- On-chip clock distribution.
- High-frequency VCOs are usually used in phase-locked loops for radio receivers.
- Ring oscillators with linear and wide tuning range are extensively used in various applications such as radar, electronic warfare, electromagnetic weapons like electromagnetic generators etc.
- Apart from communication systems, VCOs are integral part of biomedical applications as like in pacemakers.

Chapter – 2

RESEARCH PLAN

Research Objectives and Approach: Ring VCOs are often used in high-speed digital circuits for clock generation. Several reasons justify the popularity of ring VCOs are: (a) wide tuning range; (b) compatibility with digital CMOS technology and occupy substantially less area than LC oscillators; (c) the behaviour across process, supply voltage and temperature can be simulated with reasonable accuracy by standard MOS models, whereas the design of LC oscillators heavily relies on inductor and varactor models. So Ring VCO is best option for high frequency and low power consumption.

2.1 VCO Metrics:

The key metrics of a VCO consist of: oscillation frequency, tuning range, phase noise, and power consumption. The frequency of oscillation is determined by the application in which the VCO is used in, such as microprocessor or cellular phone. The tuning range is determined by the necessity of the application and the variation on oscillation frequency due to process and temperature variation. The centre frequency of some CMOS oscillators may vary by a factor of two at the extremes of process and temperature [1], thus a wide tuning range is very desirable. The design of low phase noise VCOs has become another major direction of research. The recent huge growth in wireless communication has demanded more available channels. As a result the phase noise requirement in the local oscillator becomes more stringent. In digital microprocessors, the phase noise of the oscillator will directly affect the jitter of the clock signal and the timing margin, thus limits system performance. Lastly, power consumption is extremely important for mobile applications such as cellular phones and laptops where a battery supply the power. A low power design will increase the battery life and low power designs are seen in many of the recent publications.

2.2 Research Plan:

- The existing and new proposed methods explained in [8]-[20] in which different types of delay stages are used for better performance of existing ring VCO, and is also very much useful for study of frequency characteristics of ring oscillator. One of the authors introduced two wide frequency range Voltage Controlled Ring Oscillators based on transmission gates. In transmission gate VCO wide linear

tuning frequency range capability can be obtained by adjusting resistances of transmission gates. The first proposed VCO composed of two transistor and one transmission gate. This VCO have the disadvantage of variation of the duty cycle dependent on the control voltage. The asymmetric charging and discharging is avoid by next transmission gate based VCO. In this circuit, transmission gate shift to load side so symmetric charging and discharging delay path is achieved. Other delay stage like NAND gate, XOR gate, Current-starved techniques etc. are also discussed in these papers. Several single ended ring oscillators has been analyzed .The delay is controlled by changing the current available to charge and discharge the capacitor.

- Single-ended to differential conversion for multiple-stage single-ended ring oscillators [21] and a portable high-frequency digitally controlled oscillator [22] and [23] with low power is discussed in these papers.
- Different biasing techniques are proposed [24]–[27] and discussed for the improvement of frequency in these papers.
- Low phase noise and low power operation techniques [28]-[31] of different ring VCOs are done in these papers. Analysis of frequency control techniques for inverter based ring oscillators. A brief discussion on ring oscillators and an overview of various control schemes is also presented. Drive strength controlled scheme could be used in designs sensitive to jitter and if a large tuning range is desired the coarse control scheme can be used in conjunction with one of the fine tuning schemes. For low power design the resistor control schemes are preferred.
- Design and implementation techniques with performance comparisons of Differential Ring Oscillators as CMOS Voltage Controlled Oscillators in terms of oscillation frequency, power consumption and tuning range [32]-[35].
- Jitter and phase noise in ring oscillators [36]-[38] are discussed in these papers with improvement in performance.

After the study about VCOs, there is better chance to design a low power and wide tuning frequency range ring oscillator.

2.3 Goals and Objective:

The objective is to focus on the design of a CMOS ring VCOs to improve the performance with a wide frequency tuning range. Also the applications like PLL, Frequency Synthesizers, etc. based on VCOs will be further designed and implemented.

The following goals are aimed to be achieved:

- Wide frequency tuning band
- Improved phase noise
- Increased chip density
- Less power consumption
- Low cost

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